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## (54) IMPROVEMENTS IN OR RELATING TO FLUID FLOW TRANSDUCERS

(71) I, SECRETARY OF STATE FOR DEFENCE, London, hereby the invention, for which I pray that a patent may be granted to me, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The present invention relates to fluid flow transducers.

There are many known types of fluid flowmeters depending for their operation on a variety of physical phenomena associated with the movement of fluids. Many of these types are discussed in "Flow Measurement and Control" by W. F. Coxon (Heywood & Co. Ltd). In general such known fluid flow meters are not accurately responsive to small flow rates nor do they have a sufficiently high frequency response to enable them to accurately follow sudden changes in flow rate.

It is an object of the present invention to provide a fluid flow indicator device capable of a relatively high frequency response to sudden changes in fluid flow rate and responsive to relatively small fluid flow rates.

According to the present invention a fluid flow transducer includes a passage for the flow of fluid, a flexible diaphragm tensioned so that it will only have one stable position when the fluid flow through it is negligible or insufficient, dividing the passage into an upstream region and a downstream region and having an aperture in the diaphragm which forms a constriction in the passage but allows fluid to flow from one region to the other, and detection means responsive to a deflection of the flexible diaphragm.

The diaphragm may be made of an electrically conductive material and the detection means may include an electrode positioned adjacent to but separated from the diaphragm. The electrical capacitor formed between the diaphragm and the electrode may then form an arm of a capacitance bridge or alternatively may be used as a feedback capacitor in an amplifier.

When a fluid flows through an orifice the fluid pressure on the downstream side of the orifice is less than the fluid pressure on the upstream side of the orifice; a pressure difference is required to drive the fluid through the orifice. The magnitude of the required pressure difference depends on the size and shape of the orifice and on the fluid velocity, according to known formulae of the general form:—

$$\Delta P = \frac{Q^2}{A^2 K P_2} \qquad (1)$$

where $\Delta P$ is the difference between the upstream pressure and the downstream pressure, $Q$ is the fluid flow rate, $A$ is the area of the orifice, $P_2$ is the downstream fluid pressure and $K$ is a constant.

In applications making use of this relationship for fluid flow measurement, it is conventional to use an orifice accurately machined in a comparatively thick, rigid plate, and to provide tubular connections from each side of the orifice to a liquid U-tube manometer or other pressure measuring device.

In embodiments of the present invention, the structure forming the orifice is constructed so that it also incorporates or forms a suitable electrical pressure transducer. For this purpose a flexible diaphragm is arranged to form a boundary between the fluid upstream of the orifice and the fluid downstream of the orifice, so that the pressure difference will produce a measurable deflection of the flexible diaphragm. The orifice, which determines the pressure difference for any given fluid flow rate, may be formed by an aperture in the flexible diaphragm, or alternatively it may be formed in a rigidly supported structure adjacent to and aligned with an aperture in the diaphragm. In a suitable structure the deflection of the diaphragm will have a definite relationship to the pressure difference; the relationship may be determined by the inherent stiffness of the diaphragm, or by a tensile stress or pre-loading applied to the diaphragm, or by a combination of both. Preferably the diaphragm is made thin and

light to give a useful response at comparatively high frequencies, therefore having little inherent stiffness; and it is pre-loaded with a sufficient (radially directed) tensile stress to ensure that it will return to a single stable position whenever the fluid flow is reduced to zero.

For small deflections of the diaphragm, the deflection of the diaphragm will be substantially proportional to the pressure difference causing it and will therefore be proportional to the square of the fluid flow rate ($Q^2$).

By combining the orifice structure with the pressure measuring part of the device as herein described, it is possible to make a fluid flow transducer with much less damping and a much faster dynamic response than the fixed rigid orifice plates with separate pressure transducers which are conventional in the prior art.

Embodiments of the invention will now be described by way of example only and with reference to the drawings accompanying the provisional specification of which:—

Figure 1 is a cross-section of a gas flow transducer,

Figure 2 is a block circuit diagram of a detector circuit for use with the gas flow transducer of Figure 1,

Figure 3 is a schematic circuit diagram illustrating a method of calibrating flowmeter apparatus comprising the gas flow transducer of Figure 1 and the detector circuit of Figure 2,

Figure 4 is a cross-sectional view of a modified form of deflection sensing means which may alternatively be used in the gas flow transducer of Figure 1.

Figure 5 is a cross-sectional view of parts of the gas flow transducer of Figure 1 shown prior to assembly, and

Figure 6 is a schematic drawing of an alternative form of gasc flow transducer and detector circuit.

Figure 1 shows a gas flow transducer comprising an upstream chamber 1 and a downstream chamber 2, separated by a tensioned steel diaphragm 3 which is about an inch in diameter and three thousandths of an inch thick. A circular orifice 4 in the centre of the diaphragm allows gas to flow through it from the upstream chamber 1 to the downstream chamber 2. The chamber 1 is connected to a gas inlet 5 and the chamber 2 is connected to a gas outlet 6. A capacitance type proximity detector probe 7 passes into the chamber 1 through an electrically-insulating gas-tight mounting, so that its sensing electrode 8 is positioned close to but not touching the diaphragm 3.

Figure 2 shows the detector circuit used with the gas flow transducer of Figure 1. A stable oscillator 11 is coupled by a capacitor 12 to the input of a high gain amplifier 9. The diaphragm 3 and the sensing electrode 8 (of Figure 1) are respectively connected to the input and the output of the amplifier 9, so that the capacitance between them acts as a feedback capacitance. The amplifier output is connected to a valve voltmeter circuit 13.

When gas is made to flow through the transducer through the inlet 5, chamber 1, orifice 4, chamber 2 and outlet 6, the pressure difference required to force the gas through the comparatively small orifice 4 deflects the diaphragm 3 away from the electrode 8, thereby reducing the feedback capacitance applied to the amplifier 9. The feedback capacitance between the diaphragm 3 and the electrode 8 is inversely proportional to the spacing between them. The input to the amplifier 9 from the oscillator 11 is used as a constant reference signal. The mean amplitude of the amplifier output voltage, which is measured and indicated by the valve voltmeter 13, is inversely proportional to the feedback capacitance. It follows that the voltmeter indication will tend to be an approximately linear function of the square of the fluid flow rate.

While a theoretical calculation of the response of the flowmeter to various gas flow rates can be made it is advisable to make a direct calibration against known flow rates.

One method of calibrating the flowmeter is shown in Figure 3. A gas-tight connection is made between the transducer inlet 5 and one end of a glass tube 15 which has its other end immersed in a tank of water 16. The transducer outlet 6 is connected via a solenoid-operated flow control valve 17 to a vacuum pump 18. A vacuum gauge 19 is positioned between the valve 17 and the pump 18. A pulse generator 20 has an output connected to the operating solenoid of the valve 17, and to a first vertical deflection plate $Y_1$ of a double beam cathode ray oscilloscope (CRO) 21. A second vertical deflection plate $Y_2$ of the CRO 21 is connected to an output of the amplifier 9 via the valve voltmeter 13. The amplifier 9, valve voltmeter 13, and associated parts are connected as hereinbefore described with reference to Figure 2.

In operation, with the flow control valve 17 shut, the vacuum pump 18 is adjusted to provide a convenient pressure lower than atmospheric pressure, which will be indicated by the vacuum gauge 19. The height of water in the tube 15 is noted. The pulse generator 20 is set to produce a pulse of known duration which is then applied to the operating solenoid of the flow control valve 17, and to the first vertical deflection plate $Y_1$ of the CRO 21. The solenoid opens the valve 17 for approximately the duration of the pulse, and some air is therefore drawn from the tube 15 into the pump 18 via the flowmeter. A corresponding voltage pulse is developed on the output of the amplifier 9 and is applied to the second vertical deflection plate $Y_2$ of the CRO 21. The magnitude of this pulse is noted and the new height of water in the tube 15 is also

noted. From a knowledge of the bore of the tube 15, the difference between the two heights of water and the amplitudes and duration of pulses displayed by the oscillioscope 21, the air flow rate through the flowmeter, corresponding to the measured pulse magnitude at the output of the valve voltmeter 13, can be calculated.

The process is repeated many times with a different vacuum level between the pump 18 and the valve 17 each time, and therefore a different air flow rate each time. The corresponding pulse magnitudes at the output of the valve voltmeter 13 are noted in each test. A calibration plot of flowmeter output against flow rate can then be made.

Figure 4 shows an alternative form for the capacitance probe (7 in Figure 1) wherein the probe electrode 8 is surrounded by an annular guard ring electrode 22 which is electrically insulated from the electrode 8 and from the transducer structure. In operation the electrodes 8 and 22 are kept at the same electrical potential thus ensuring that the electrostatic field between the electrode 8 and the diaphragm 3 of the flowmeter is substantially uniform.

Figure 5 shows details of a clamping arrangement for tensioning the diaphragm 3 to ensure that the diaphragm will only have one flat, stable position when the gas flow rate is zero. This arrangement comprises an annular ridge 25 on a clamping face of one of the chambers 1 or 2 and a corresponding annular channel 26 on the clamping face of the other chamber. When the chambers 1 and 2 and the diaphragm 3 are clamped together in this arrangement the diaphragm 3 is tensioned as the bolts are tightened.

The gas flowmeter described hereinabove with reference to Figures 1 and 2 and calibrated in accordance with the method illustrated by Figure 3 has a frequency response useful up to 500 Hz. It can also be made to measure gas flow rates of the order of 0.02 grams/second. It is therefore very suitable for measuring small pulses of gas flow, such as are used, for example, in the attitude control systems of space craft.

In Figure 6 an alternative form of flowmeter is shown. It comprises a passage for gas 27 divided by a thin circular lightly tensioned electrically conductive diaphragm 28 having an orifice 29 at its centre.

Two annular electrodes 30 and 31 are rigidly supported in the passage 27, with their central portions protruding close to but equally spaced from opposite sides of the part of the diaphragm surrounding the orifice 29. The inner surfaces of the electrodes 30 and 31 and the orifice 29 are shaped and positioned so that in combination they form an orifice having shape and proportions substantially similar or equivalent to the form of an orifice in a conventional orifice plate. There are a number of comparatively large perforations in the outer parts of the electrodes 30 and 31, to allow the pressures in the two parts of the passage 27 (upstream and downstream from the orifice) to act directly on most of the surface area of the diaphragm and to avoid any substantial damping occurring due to gas trapped between the diaphragm 28 and the electrodes 30 and 31, which would adversely affect the dynamic response of the transducer.

The electrodes 30 and 31 are electrically insulated from each other, and are connected so that the capacitances formed between the diaphragm 28 and the two electrodes 30 and 31 respectively form two adjacent arms of an alternating-current capacitance bridge circuit. The other two arms of the bridge are formed by equal fixed capacitors 32 and 33. An alternating voltage generator 34 is connected to one pair of opposite terminals of the bridge. The output of the amplifier 35 is connected to the other pair of opposite terminals of the bridge. The output of the amplifier 35 is connected to an alternating current voltmeter 36.

The bridge circuit is approximately balanced when the gas flow rate is zero and the diaphragm in a stable rest position. When gas is made to flow through the transducer, it deflects the diaphragm 28, which increases the capacitance between the diaphragm and the electrode 31 and reduces the capacitance between the diaphragm and the electrode 30. This unbalances the bridge and causes the mean amplitude of the output of the amplifier 35 to change. This amplitude is measured and indicated by the voltmeter 36. The flowmeter can be calibrated (for instance as hereinbefore described with reference to Figure 3) so that the voltmeter readings can be used as measurements of the gas flow rate.

The diaphragm 28 may be tensioned in the assembly of the transducer by starting with a larger circle of the diaphragm material clamped between two rings (not shown) of inside diameter greater than the outside diameter of the transducer structure. The parts of the transducer on one side of the diaphragm are assembled so that the plane in which the diaphragm is to lie is horizontal, and the diaphragm laid over them so that it supports the weight of the two clamping rings. This puts the diaphragm in tension, if the weight of the rings is suitably chosen. The other half of the transducer structure is then assembled and clamped over the diaphragm (by bolts or other means not shown). The two clamping rings can then be removed, and the excess diaphragm material trimmed away.

A typical transducer of the kind shown in Figure 6 was made with an orifice of 0.625 inch minimum inside diameter in a gas passage of two inches inside diameter. The diaphragm was formed of anodised aluminium alloy one-hundredth of an inch thick, and the capacitance in each arm of the bridge circuit was about ten picofarads. This was capable of

measuring air or oxygen flow rates up to 200 litres per minute and had a response substantially independent of frequency up to a frequency of about 70 Hz.

Clearly many variations of this invention are possible. For instance the sensing electrode 8 in Figure 1 may be replaced by an electrode constructed like one of the electrodes 30 or 31 in Figure 6. A different form of proximity detector circuit may be used to detect and measure the deflection of the diaphragm; indeed the proximity detector circuit may be of the inductive rather than the capacitance type.

WHAT I CLAIM IS:—

1. A fluid flow transducer including a passage for the flow fluid, a flexible diaphragm tensioned so that it will only have one stable position when the fluid flow through it is negligible or insignificant, dividing the passage into an upstream region and a downstream region and having an aperture in the diaphragm which forms a constriction in the passage but allows fluid to flow from one region to the other, and detection means responsive to a deflection of the flexible diaphragm.

2. A fluid flow transducer as claimed in claim 1 and wherein the diaphragm is made of an electrically conductive material, and the detection means includes an electrode positioned adjacent to but separated from the diaphragm and a circuit responsive to changes in the electrical capacitance formed between the electrode and the diaphragm.

3. A fluid flow transducer as claimed in claim 1 or claim 2 and wherein the aperture in the flexible diaphragm is aligned with and forms part of an orifice assembly which also includes parts rigidly supported in the passage.

4. A fluid flow transducer substantially as hereinbefore described with reference to Figures 1 and 2, or Figures 1, 2 and 4, or Figures 1, 2, 4 and 5, or Figure 6 of the drawings accompanying the provisional specification.

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Agent for the Applicant.

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1353197 PROVISIONAL SPECIFICATION
2 SHEETS *This drawing is a reproduction of the Original on a reduced scale*
Sheet 1

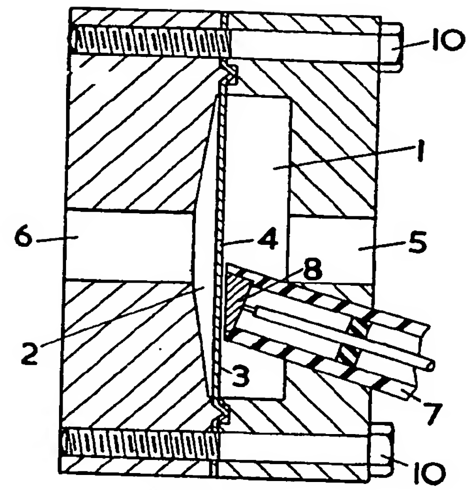


FIG. 1.

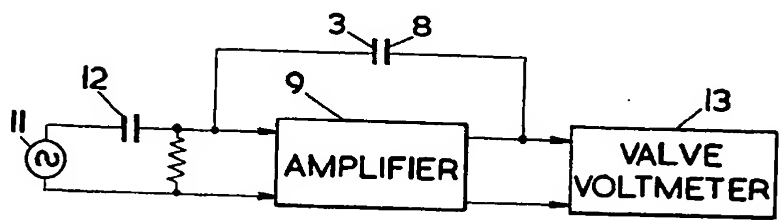


FIG. 2.

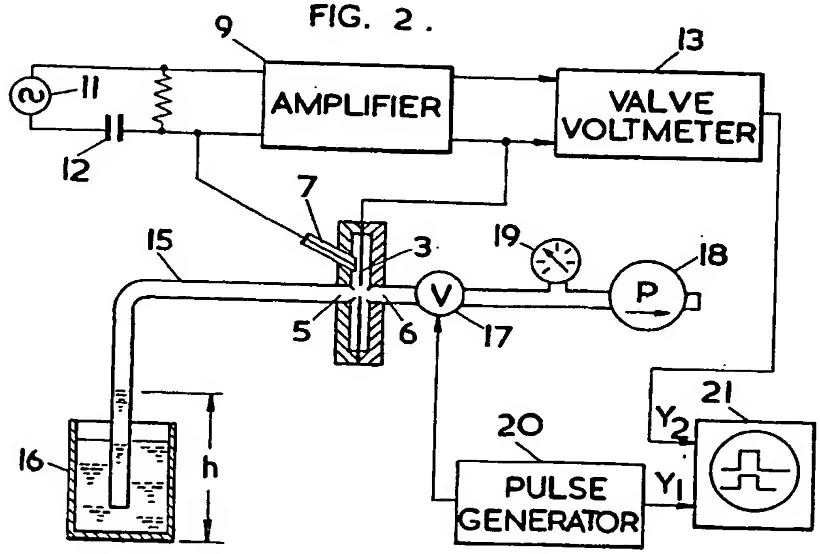


FIG. 3.

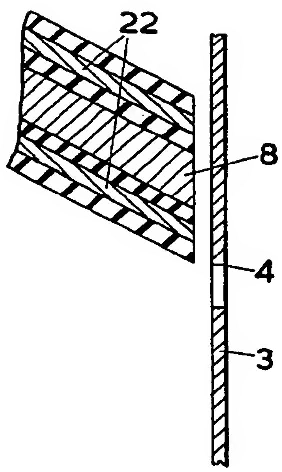


FIG. 4.

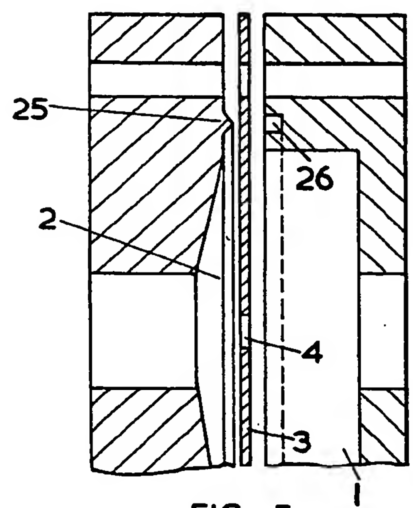


FIG. 5.

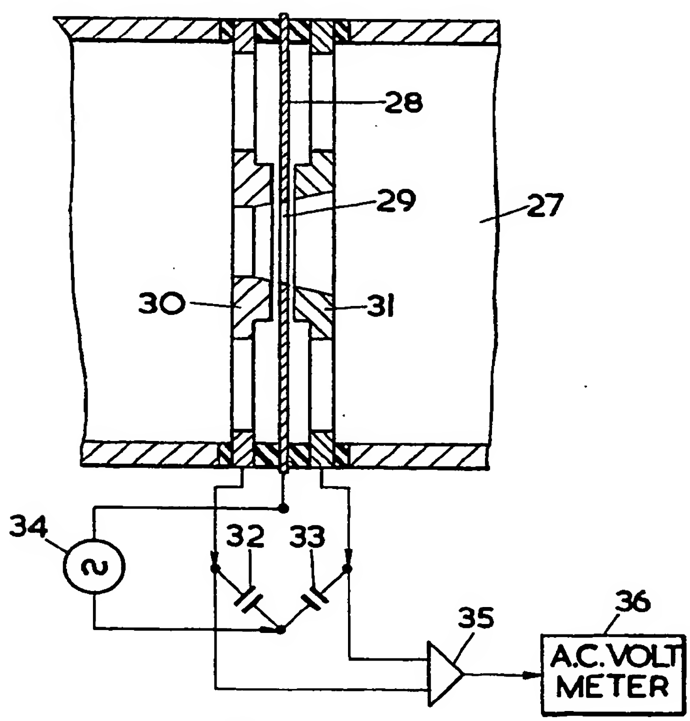


FIG. 6.